THE TILT OF THE FUNDAMENTAL PLANE: THREE-QUARTERS STRUCTURAL NONHOMOLOGY, ONE-QUARTER STELLAR POPULATION

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ABSTRACT

The variation of the mass-to-light ratios M/L of early type galaxies as function of their luminosities L is investigated. It is shown that the tilt $\beta = 0.27$ (in the B–band) of the fundamental plane relation $M/L \propto L^{\beta}$ can be understood as a combination of two effects: about one-quarter (i.e. $\Delta\beta = 0.07$) is a result of systematic variations of the stellar population properties with increasing luminosity. The remaining three-quarters (i.e. $\Delta\beta = 0.2$) can be completely attributed to nonhomology effects that lead to a systematic change of the surface brightness profiles with increasing luminosity. Consequently, the observed tilt in the K–band ($\beta = 0.17$) where stellar population effects are negligible, is explained by nonhomology effects alone. After correcting for nonhomology, the mean value of the mass-to-light ratio of elliptical galaxies (M/L_B) is 7.1±2.8 (1σ scatter).

Subject headings: galaxies: clusters: general — galaxies: interactions — galaxies: structure — galaxies: photometry — galaxies: fundamental parameters

1. Introduction

Traditionally, the global properties of elliptical galaxies have been characterized by three observables: the central velocity dispersion σ_0, the effective or half-light radius r_e, and the mean surface brightness within the effective radius I_e. It is generally assumed that elliptical galaxies are relaxed particle systems. From a theoretical point of view, the virial theorem then predicts a relationship between the gravitational mass, the velocity dispersion and the radius. This can be written as a relationship between I_e, σ_0 and r_e. These observables should then be constrained to a two-dimensional plane in the above three-space. Elliptical galaxies are indeed found to lie along a plane; however, the observed plane (popularly known as the fundamental plane [FP]; Djorgovski & Davis 1987, Faber et al. 1987, Dressler et al. 1987) deviates from the prediction using a constant M/L. This deviation is known as the "tilt" of the FP. Since the above prediction is based on the assumption that the mass–to–light ratio and the global structure of the elliptical galaxies are not dependent on the luminosity, the explanations for the tilt have been attributed to deviations from one or both of these hypotheses.

Following on that, Faber et al. (1987) suggested that the M/L values increase systematically with increasing luminosity. Using this interpretation, the observed averaged value of the FP tilt over a large group of galaxy samples in the B–band is written as $M/L \propto L^{\beta}$, with β=0.27±0.08 (Prugniel & Simien 1996). Since brighter ellipticals are systematically redder, at least part of the tilt must be understood as stellar population variations along the different luminosities of elliptical galaxies. However, the presence of a "remaining" tilt (β=0.17±0.01) in the K–band FP

(Pahre, Djorgovski & de Carvalho 1998), where population variations are weak, implies that this solution alone cannot explain completely the observed slope. In fact, the variation in the properties of the stellar population as deduced from broad band colors and the Mg_2 index explain only one-third of the slope, i.e., $\Delta\beta \sim 0.10$ in the B-band (Tinsley 1978, Dressler et al. 1987, Prugniel & Simien 1996). We show this more explicitly in Figure 1a, where the luminosity dependence of estimated stellar M/L ratios in B (open circles) and K-bands (filled circles) is plotted for a sample of 911 morphologically selected early-type galaxies from the Sloan Digital Sky Survey (SDSS) Early Data Release and the Two Mass All Sky Surveys (2MASS) (Bell et al. 2003). The dependence of stellar M/L ratios on galaxy luminosity is weak in the B-band, in line with previous studies, and is negligible in the K-band. Taken together, the above is consistent with the conclusion that the dominant part of the tilt of the FP ($\Delta\beta \sim 0.2$) is not a population effect.

Changes in the mixture of dark-to-visible matter as function of luminosity would be a plausible explanation for the remaining tilt. However, observations (Romanowsky et al. 2003) demonstrate that the amount of dark matter within an effective radius is in general negligibly small. Furthermore, systematic variations in kinematical structure (van der Marel 1991, Bender, Burstein and Faber 1992, hereafter BBF) and radial anisotropy (Ciotti, Lanzoni & Renzini 1996, Ciotti & Lanzoni 1997) cannot produce the observed tilt. The role played by rotation is also small (Busarello et al. 1997).

In this Letter, we argue that the remaining tilt of the FP is due to a systematic variation of the structural (and its associated dynamical) nonhomology of the elliptical galaxies as function of their luminosity. Following an analogy with the FP of the globular clusters, Djorgovski (1995) suggested a systematic change in the galaxy concentration as a viable hypothesis. Hjorth & Madsen (1995) explained part of the tilt of the FP ($\Delta\beta = 0.12$) using a galaxy model with a variable central gravitational potential correlated with the luminosity. Following a similar idea but using a model directly related with the observations (the Sérsic (1968) $r^{1/n}$ law), Ciotti et al. (1996) suggested that a suitable variation (by a factor of $\sim$ 2–4) of the shape parameter n (i.e. a different degree of concentration) along the FP would be able to explain the tilt. However, Prugniel & Simien (1997) (and see also Graham & Colless (1997) in the V–band) showed that the structural nonhomology contributes only $\Delta\beta \sim 0.06 - 0.08$ and to fully account for the tilt of the FP they needed to include some contributions from stellar population and rotational support. These analysis could be affected by a limited sample which had a small range in Sérsic indices $2\lesssim n\lesssim 5$ which is far from providing the full range of nonhomology observed by other authors with $1\lesssim n\lesssim 10$ in the same absolute magnitude range $-22\lesssim M_B\lesssim -15$ (see e.g., Graham & Guzmán 2003).

Taking into account the full range of structural nonhomology observed, we quantify the contribution to the tilt from the structural nonhomology in the B band. We show that the structural nonhomology is able to explain $\approx$3/4 of the tilt in the B–band (i.e. $\Delta\beta$=0.2), which, in combination with the tilt expected from population variations (i.e. $\Delta\beta\sim$0.1) can explain completely the observed tilt of the FP.

2. The scalar virial theorem and the FP tilt

We use the identity

$$L = c_1 I_e r_e^2 \tag{1}$$

and the scalar virial theorem for a stationary stellar system

$$GM = c_2 \sigma_0^2 r_e \tag{2}$$

with L being the luminosity, G the gravitational constant, M the mass and c_1 and c_2 structure terms. Any stellar system in virial equilibrium is then expected to follow the identity:

$$r_e = G^{-1}(c_2 c_1^{-1})(M/L)^{-1}\sigma_0^2 I_e^{-1}. \tag{3}$$

With the definition given in the Introduction for I_e, $c_1 = 2\pi$. The FP (Dressler et al. 1987; Djorgovski & Davis 1987) in the B–band can be fitted by:

$$r_e \propto (\sigma_0^2)^{0.7} I_e^{-0.85}. \tag{4}$$

This relation is a consequence of the variation of $c_2^{-1}(M/L)$ with L.[1] If, following Faber et al.

[1] In the more general case, $c_2^{-1}(M/L)=L^{\beta} I_e^{\gamma}$, γ has been found to be compatible with 0 ($\gamma = -0.01 \pm 0.13$; Prugniel & Simien 1996) and in what follows we will assume $\gamma = 0$.

(1987), c_2 is constant elliptical galaxies would be structurally homologous systems and the tilt would have to be explained as a systematic variation of mass–to–light (M/L) ratio with luminosity: $M/L \propto L^{\beta}$, with β=0.27±0.08.

As discussed in the Introduction it is unlikely that this tilt can be explained by stellar population effects alone. One needs to combine two well known observations: the systematic variation of stellar populations with luminosity and the change of observed structural properties along the early-type sequence from dwarf to giant ellipticals. Ideally both effects in combination would be able to account for the full tilt of the FP.

3. The relation between c_2 and n

It has been shown (see e.g. Trujillo, Graham & Caon 2001 and references therein) that elliptical galaxies do not form a homologous structural family and that the luminosity–dependent departures from the $r^{1/4}$ law can be described by the $r^{1/n}$ Sérsic model. The nonhomology is also reflected in the strong correlations between the shape parameter n and photometric–independent galaxy properties as, for example, the central velocity dispersion (Graham, Trujillo & Caon, 2001).

In Fig. 1b, we show the relation between the shape index n and the absolute B–band (model–independent) magnitude for 200 elliptical galaxies. The galaxies used in this plot correspond to ellipticals from the Virgo, Fornax and Coma Clusters (Caon et al. 1990; Caon, Capaccioli & D'Onofrio 1994; Binggeli & Jerjen 1998; Gutiérrez et al. 2004). Those galaxies classified as S0 were removed from our sample to avoid possible miss-measurements of the index n due to the disk component of these galaxies. Error estimates for n are found to have a typical uncertainty of 25% (Caon, Capaccioli & D'Onofrio 1993). The high statistical significance of this correlation has been studied in previous papers (see, e.g. Graham et al. 2001). To check that the robustness of the above relation is not affected by the large number of faint galaxies, we have evaluated the Spearman correlation coefficient for those galaxies brighter than M_B=-16.5 (H_0=70 km s^{-1} Mpc^{-1}) and we find r_s=0.72.

Using the Sérsic model, it is possible to relate the structural parameter c_2 with n, leading also to a relation between n and L, or between c_2 and L. To estimate c_2 for a Sérsic model we need to evaluate the velocity dispersion profile $\sigma_r(r)$. In the most simple case this can be done by assuming a spherical, nonrotating, isotropic $r^{1/n}$ model and then evaluating $\sigma_r(r)$ using the Jeans equation (see, e.g., Binney & Tremaine 1987). However, the observed central velocity dispersion σ_0 that enters in Eq. 2 does not correspond to $\sigma_r(0)$, but rather to the observed projected velocity dispersion $\sigma_p(R)$, luminosity averaged over the aperture used for the spectrographic observations $\sigma_{ap}(R_{ap})$. Consequently, to evaluate properly c_2, we need to switch from $\sigma_r(r)$ to $\sigma_p(R)$ and from this to $\sigma_{ap}(R_{ap})$ (see a detailed explanation e.g. in Sec. 2.2 of Ciotti et al. 1996).

To illustrate how c_2 changes depending on which estimate of the velocity dispersion is used we show in Fig. 2 the relation between c_2 and n derived from $\sigma_r(r_e/8)$, $\sigma_p(r_e/8)$ and $\sigma_{ap}(r_e/8)$. We show c_2 for $r = r_e/8$ because this is one of the most usual aperture radii to measure σ_0 (Jørgensen, Franx & Kjærgaard 1993). Our value of c_2 is in good agreement with the estimates of this quantity by other authors (e.g. Prugniel & Simien (1997), Bertin, Ciotti & Del Principe, 2002).

Since the sizes of galaxies differ from one another and because galaxies are observed at different distances, the estimation of the central velocity dispersion using a fixed angular aperture samples different fractions of the total light (or the effective radii). Consequently, when dealing with samples that extend over a large range of sizes, it is not the best approximation to estimate c_2 from the observations by using a fixed aperture related to the effective radius (e.g. $r_e/8$). Instead one should use typical angular apertures (e.g. $1.''6$ or $2.''2$).

In order to evaluate the influence of nonhomology in the FP, we have selected from the sample of elliptical galaxies presented above those galaxies that have a measured central velocity dispersion. The velocity dispersions are obtained from Hypercat. This leaves us with a total of 45 galaxies ranging from -15 to -22 in the B–band. In Fig. 2 we show the c_2 values for the galaxies of this subsample estimated using two different fixed realistic apertures $1.''6$ and $2.''2$. As we can see in this figure, the effect of changing the aperture from $1.''6$ to $2.''2$ is not dramatic. In what follows we will use the mean value of these two measure-

ments $c_2(1.''6)$ and $c_2(2.''2)$ as an estimate of the true value of c_2 for our observed galaxies.

4. The tilt of the FP

Fig. 3 shows the relation between M/L and the luminosity L for the selected galaxies, taking into account the variation in c_2 as a result of variations in shape parameters n. For comparison, in the same figure we also show the result for a constant value for c_2, i.e. if structural homology is assumed to hold. The value we have used for c_2=4.86 in the assumption of homology is taken to match the value presented in BBF for a King model with r_t/r_c ~100. This value is quite close to the value expected for a de Vaucouleurs law (n=4; c_2=4.6).

Fig. 3 shows that the relationship between the M/L and L is much flatter if the nonhomology is accounted for. To quantify this change we have performed a minimum χ^2 fit to the data distributions using the relation $(M/L) = \alpha L^{\beta}$. The values are $\beta = 0.10(\pm 0.04)$ if nonhomology is addressed and $\beta = 0.29(\pm 0.04)$ for the homologous case. The exponent β for the homologous case in the B-band is in excellent agreement with the values reported previously. On the other hand, we can see that the nonhomology part of the tilt accounts for $\Delta\beta \sim 0.2$. We have also checked if the incompleteness is playing a role at the fainter luminosities. Our sample is 90% complete down M_B=-17. If we remove from our analysis all the galaxies below this limit we get the following exponents: $\beta = 0.27(\pm 0.04)$ for the homologous case and $\beta = 0.06(\pm 0.04)$ in the nonhomologous case. Again, we find that the nonhomology part of the tilt accounts for $\Delta\beta \sim 0.2$.

5. Discussion

It is encouraging that the tilt $\beta \sim 0.1$ of the FP after correction for to nonhomology is in very good agreement with the value expected due to systematic variations of stellar population properties of elliptical galaxies ($\Delta\beta \sim 0.07$). The observed tilt of $\beta = 0.29(\pm 0.04)$ in the B–band FP therefore can be understood as a combination of three-quarters structural nonhomology and one-quarter stellar population effects. The tilt of the K–band FP where the change in the stellar population is negligible is approximately $\beta = 0.2$. This is indeed in good agreement with our expectation if the tilt were due only to the nonhomology and if color gradients inside galaxies do not change their Sérsic indices. Indeed, radial V–K gradients in the surface brightness profiles of ellipticals are on average only 0.16 mag dex^{-1} (Peletier, Valentijn & Jameson 1990) which is small compared to the variations in surface brightness within an effective radius. The homologous FP of our sample has a scatter in log(M/L) of order 25% which is consistent with previous results (BBF; Pahre, Djorgovski & Carvalho 1998). The scatter is not significantly reduced in the non-homologous FP which indicates that it is mainly a result of population effects and not of structural variations within a given luminosity bin.

Our results rule out that even very massive ellipticals are strongly dominated by dark matter in their inner regions, which is in agreement with Rix et al. (1997) and Gerhard et al. (2001). After correcting for nonhomology, the mean value of the mass-to-light ratio (M/L_B) of early-type galaxies in our luminosity range is 7.1±2.8 (1σ scatter). This value is in good agreement with the value expected for an old stellar populations of M/L_B=7.8±2.7 (Gerhard et al 2001).

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REFERENCES

Bell, E.F., McIntosh, D.H.,Katz, N., Weinberg, M. D., 2003, ApJS, in press (astro-ph/0302543)

Bender, R, Burstein, D., & Faber, S.M., 1992, ApJ, 399, 462

Bertin, G., Ciotti, L., Del Principe, M., 2002, A&A, 386, 149

Binggeli, B., & Jerjen, H., 1998, A&A, 333, 17

Binney, J., Tremaine, S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton.

Busarello, G., Capaccioli, M., Capoziello, S., Longo, G., & Puddu, E., 1997, A&A, 320, 415

Caon, N., Capaccioli, M., & Rampazo, R., 1990, A&AS, 86, 429

Caon, N., Capaccioli, M., & D'Onofrio, M., 1993, MNRAS, 265, 1013

Caon, N., Capaccioli, M., & D'Onofrio, M., 1994, A&AS, 106, 199

Ciotti, L., Lanzoni, B., & Renzini, A., 1996, MNRAS, 282, 1

Ciotti, L. & Lanzoni, B., 1997, A&A, 321, 724

Djorgovski, S. & Davis, M., 1987, ApJ, 313, 59

Djorgovski, S., 1995, ApJ, 438, L29

Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R. & Wegner, G., 1987, ApJ, 313, 42

Faber, S. M., Dressler, A., Davies, R. L., Burstein, D., Lynden-Bell, D., Terlevich, R. & Wegner, G., 1987, in Nearly normal galaxies: From the Planck time to the present, ed. S.M. Faber (NY: Springer), 175

Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950

Gerhard, O., Kronawitter, A., Saglia, R., & Bender, R., 2001, AJ, 121, 1936

Graham, A. W., & Colless, M., 1997, MNRAS, 287, 221

Graham, A. W., Trujillo, I., Caon, N., 2001, AJ, 122, 1707

Graham, A. W., & Guzmán, 2003, ApJ, 125, 2951

Gutiérrez, C.M., Trujillo, I., Aguerri, J.A.L., Graham, A.W., Caon, N., 2003, ApJ, in press

Hjorth, J. & Madsen, J., 1995, ApJ, 445, 55

Jørgensen, I., Franx, M., & Kjærgaard, P., 1993, ApJ, 411, 34

Pahre, M. A., Djorgovski, S. G. & de Carvalho, R. R., 1998, AJ, 116, 1591

Peletier, R. F., Valentijn, E. A., & Jameson, R. F., 1990, A&A, 233, 62

Prugniel, Ph., & Simien, F., 1996, A&A, 309, 749

Prugniel, Ph., & Simien, F., 1997, A&A, 321, 111

Rix, H-W, de Zeeuw, P. T., Cretton, N., van der Marel, R. P., Carollo, C. M., 1997, ApJ, 488, 702

Romanowsky, A. J., Douglas, N. G., Arnaboldi, M., Kuijken, K., Merrifield, M. R., Napolitano, N. R., Capaccioli, M. & Freeman K.C., 2003, Science, 301, 1696

Salpeter, E. E. 1955, ApJ, 121, 161

Sérsic, J. 1968, Atlas de Galaxias Australes Córdoba: Obs. Astronómico

Tinsley, B.M., 1978, ApJ, 222, 14

Trujillo, I., Graham, A. & Caon, N., 2001, MNRAS, 326, 869

van der Marel, R., 1991, MNRAS, 253, 710

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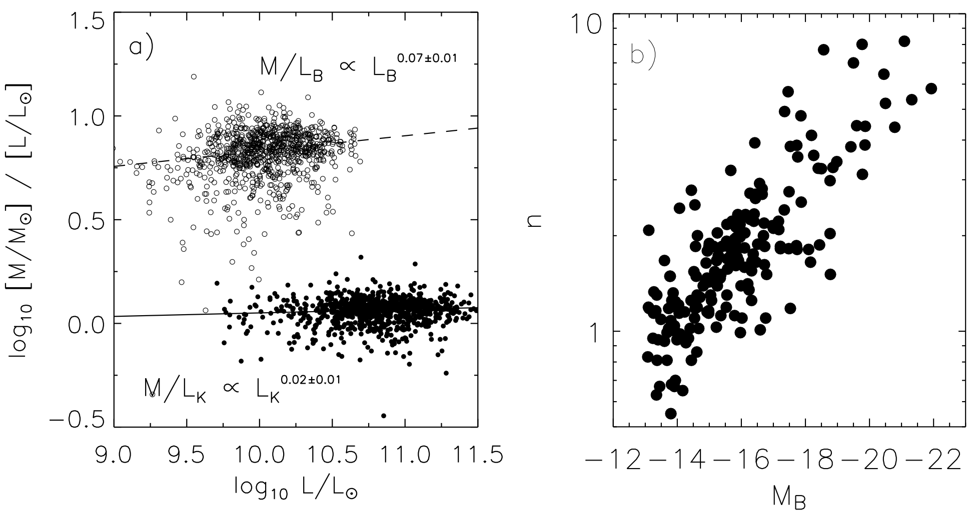

Fig. 1.— (*a*) Luminosity dependence in stellar M/L ratios in the B-band (open circles) and the K-band (filled circles) from 911 morphologically selected early-type galaxies ($14.5 < r < 16.5; K < 13.6; r_e > 2$") from a combined SDSS/2MASS galaxy catalog. The stellar M/L ratios are estimated using a Salpeter (1955) IMF, and using observed galaxy colors to place constraints on the range of plausible stellar M/L ratios, allowing for generous variations in galaxy stellar population age and metallicity. The B-band luminosities and M/L ratios were estimated using stellar population model transformations using the PEGASE code (see Fioc & Rocca-Volmerange 1997 for an earlier version of the code that we use). The lines show robust fits to the trends, where points more than 2.5σ from the trends are excluded from the fits. (b) Sérsic index n of elliptical galaxies as a function of their absolute magnitude.

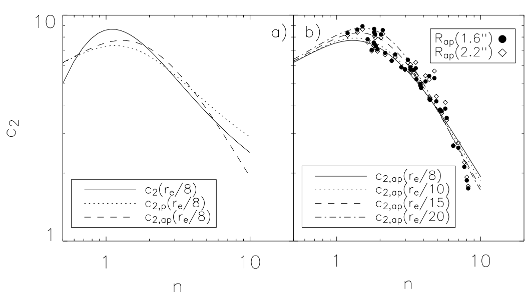

Fig. 2.— (a) Estimated virial coefficient c_2 for a Sérsic model based on an aperture radius $r_e/8$; c_2 is obtainted by using the velocity radial profile $\sigma_r(r)$, the projected radial profile $\sigma_p(R)$ and the projected aperture radial profile $\sigma_{ap}(R_{ap})$. (b) Estimated values of c_2 for two different fixed angular apertures ($1.''6$ and $2.''2$). Overplotted are the expected c_2-values for different apertures.

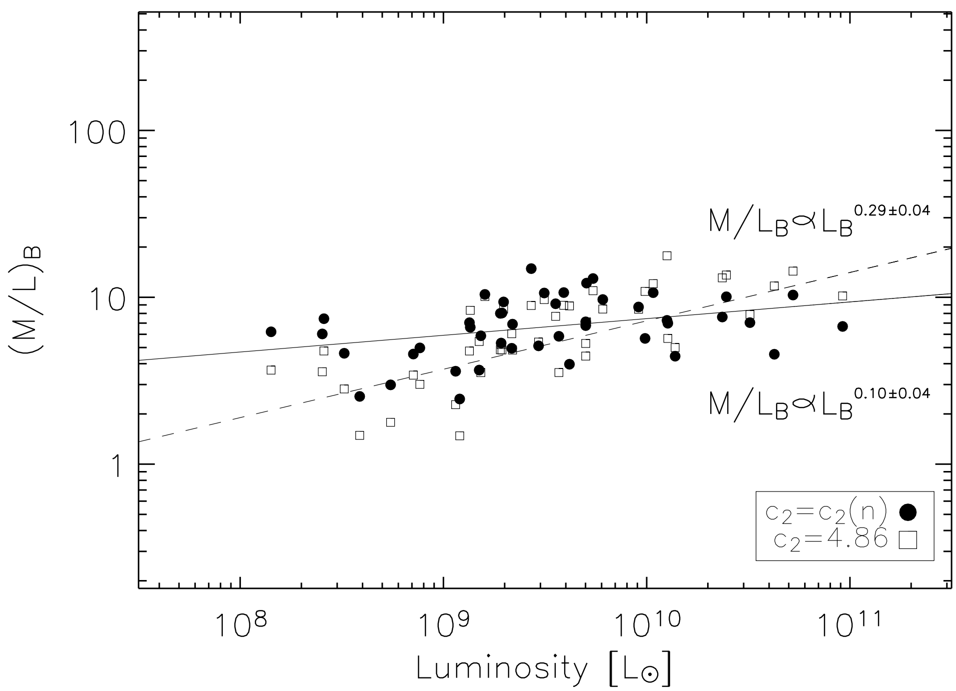

Fig. 3.— Relation between the M/L ratio and L for our selected galaxies. The filled circles represent the relation between the M/L ratio and L when c_2 accounts for variations in the observed value of n (i.e. the nonhomology) of elliptical galaxies. The open squares represent the relation between M/L and L when c_2 is to assumed to have a constant value (i.e., homology) equal to the value used for a King model with r_t/r_c ~100 proposed by BBF. Note that to transform from the units in that paper to ours, we must make the transformation c_2=4.3$c_{2,BBF}$.